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“SWIFT Observations in the Sea State DRI”

Encl: (1) Final Report including publications for “SWIFT Observations in the Sea State DRI” with accompanying SF 298.  
(2) Publication in Eos, 23 January 2017: “The Balance of Ice, Waves, and Winds in the Arctic Autumn.”

Enclosed please find the Final Report with publications and corresponding SF 298 form (1) & (2) for the subject grant. These documents constitute the Final Technical Report and deliverables for ONR Grant N00014-13-1-0284.

cc: ONR Seattle – Robert Rice and Benjamin Blake  
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## Final Report

### **SWIFT Observations in the Sea State DRI**

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## **MAJOR GOALS**

The major goal is to improve understanding of the processes governing the sea state and air-sea interactions of the Arctic Ocean. The processes can then be correctly parameterized for inclusion in forecast models for the Arctic region. The end goal is thus to improve Arctic (and global) predictions through a more realistic representation of the ice-ocean-atmosphere physics.

## **OBJECTIVES**

The overall objective is to measure wave-ice interactions in the Arctic for the calibration and improvement of forecast models. The specific objectives are to understand the processes controlling ice formation and the role of storms in driving exchange between the atmosphere, sea ice, and the ocean.

## **APPROACH**

The technical approach is to deploy SWIFT buoys during storms in the Arctic, in close coordination with satellite remote sensing acquisitions and forecast models. The SWIFT measure winds, waves, turbulence, temperature, and salinity at the ocean surface. Using an array of SWIFTs enables the observation of spatial gradients, in particular the attenuation of waves propagating through sea ice. These measurements are combined with shipboard profiles of upper ocean to determine surface heat exchange and the role of winds and waves in ice formation.

## **WORK COMPLETED**

The complete project (FY13-FY17) was completed in three phases. The planning phase (FY13) culminated in the publication of a detailed science plan (Thomson et al, 2013). The observational phase (FY14-FY15) culminated in a 6-week expedition onboard the R/V Sikuliaq and the collection of a comprehensive data set during a variety of wave-ice conditions. The analysis phase (FY16-FY17) has synthesized these data in a series of publications, including the definition of a sea state climatology (Thomson et al, 2016) and a summary of the field expedition (Thomson et al, 2017).

## RESULTS

The main result has been the growing significance of surface waves in the Arctic. This is evident in the prevalence of pancake ice during the field expedition and in the long-range propagation of waves into the sea ice (Cheng et al, 2017). Other results include the importance of surface winds and waves in mixing ocean heat up to the surface for release during ice formation.

## IMPACT/APPLICATIONS

The calibration of wave-ice interactions in WAVEWATCH3 has dramatically improved skill of the model for future applications (Rogers et al, 2016). The generation of a comprehensive dataset on surface fluxes and ice formation will enable the continued calibration and testing of next generation models.

## RELATED PROJECTS

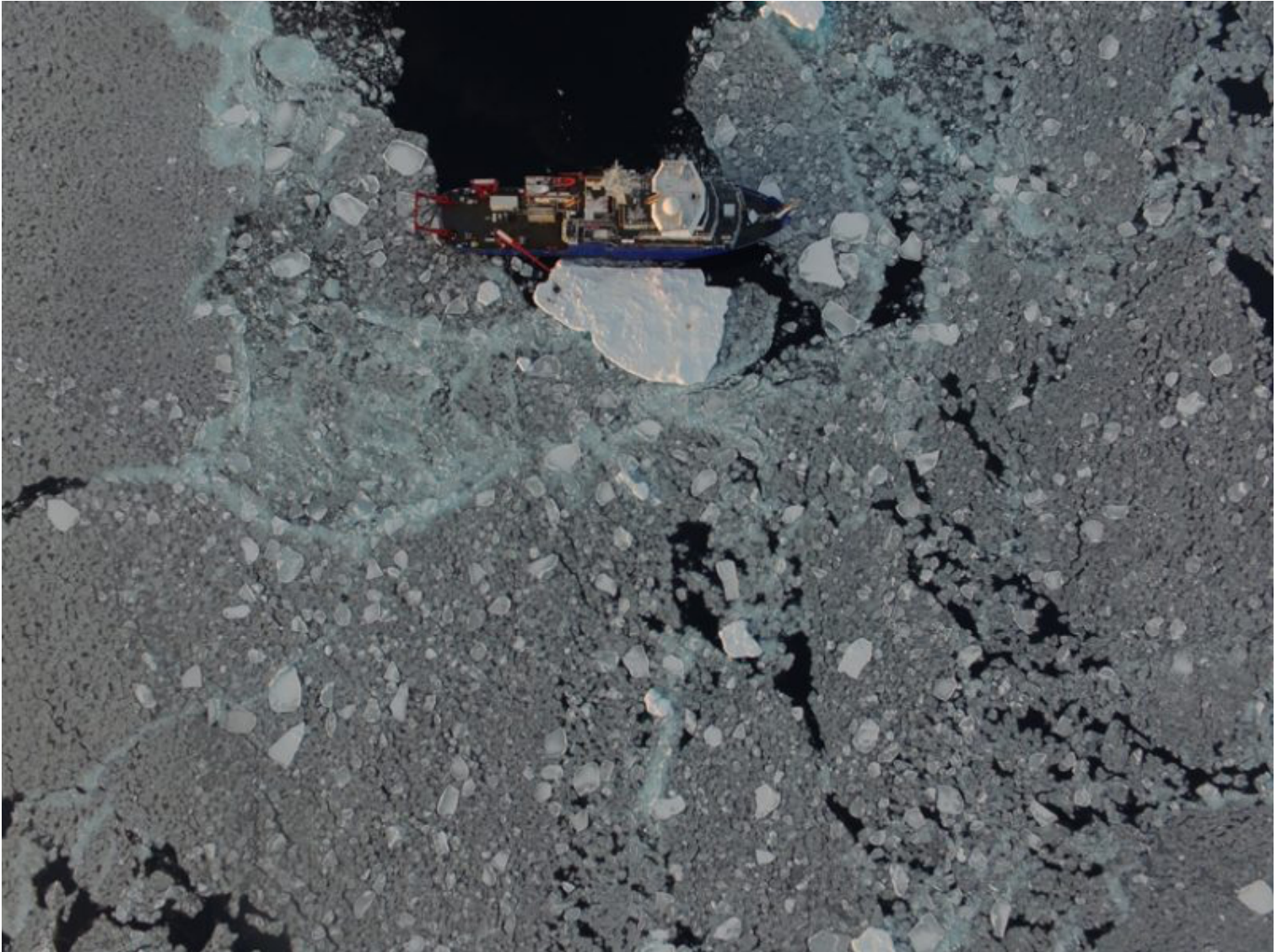
The Arctic Sea State project has extended and continued several lines of research initiated during the Marginal Ice Zone program that preceded it: [www.apl.uw.edu/miz](http://www.apl.uw.edu/miz). The two programs were presented as an integrated review in Lee and Thomson (2017).

## PUBLICATIONS

- Cheng et al, Calibrating a viscoelastic sea ice model for wave propagation in the Arctic fall marginal ice zone, *J. Geophys. Res.*, **122** (2017). [published, refereed]
- Lee, C., and J. Thomson, An Autonomous Approach to Observing the Seasonal Ice Zone, *Oceanography Magazine*, **30** (2017). [published, refereed]
- Thomson, J., S. Ackley, H. H. Shen, and W. E. Rogers, The balance of ice, waves, and winds in the Arctic autumn, *Eos*, <https://eos.org/project-updates/the-balance-of-ice-waves-and-winds-in-the-arctic-autumn>, **98** (2017). [published, refereed]
- Ardhuin et al, Measuring ocean waves in sea ice using SAR imagery: A quasi-deterministic approach evaluated with Sentinel-1 and in situ data, *Remote Sensing of Environment*, **189** (2017). [published, refereed]
- Collins et al, Doppler Correction of Wave Frequency-Spectra Measured by Underway Vessels, *J. Atmos. & Ocean. Tech.*, **34** (2017). [published, refereed]
- Rogers, E., J. Thomson, H. Shen, M. Doble, S. Cheng, P. Wadhams, Dissipation of wind waves by pancake and frazil ice in the autumn Beaufort Sea, *J. Geophys. Res.*, **121** (2016). [published, refereed]
- Thomson et al., Emerging trends in the sea state of the Beaufort and Chukchi Seas, *Ocean Modelling*, **105** (2016). [published, refereed]
- Thomson, J., V. Squire, S. Ackley, P. Wadhams, A. Babanin, P. Guest, T. Maksym, S. Stammerjohn, C. Fairall, O. Persson, M. Doble, E. Rogers, H. Graber, H. Shen, J. Gemmrich, S. Lehner, B. Holt, and T. Williams, *Science and Experiment Plan: Sea State and Boundary Layer Physics of the Emerging Arctic Ocean*, Technical Report APL-UW 1306, Applied Physics Laboratory, University of Washington, Seattle, September 2012, 59 pp (**2013**). [published]

# The Balance of Ice, Waves, and Winds in the Arctic Autumn

Although summer sea ice loss in the Arctic is well studied, less is known about how ice comes back in autumn. A new program is changing that.



The R/V *Sikuliaq* is surrounded by new pancake ice (gray) and remnants of multiyear ice (white) during an “ice station,” when the ship stopped at an ice floe immediately following a wave event on 17 October 2016. This photo was taken using a DGI Phantom unmanned aerial system. Credit: Guy

Williams (University of Tasmania/ACE CRC) and Ted Maksym (WHOI)

By Jim Thomson, Stephen Ackley, Hayley H. Shen, and W. Erick Rogers © 23 January 2017

One of the most notable signals of rapid change in the Arctic is the loss of sea ice during summer months [*Jeffries et al.*, 2013; *Wang and Overland*, 2012]. Not only does the ice cover less area during the summer, it's also growing thinner [e.g., *Stroeve and Notz*, 2015]. Scientists have focused on studying the mechanisms responsible for summer ice loss, but they've paid less attention to the recovery of the sea ice in the autumn.

Most icebreaker-based research activity in the Arctic concludes by late September each year, resulting in a shortage of data for the autumn months. A new program, Sea State and Boundary Layer Physics of the Emerging Arctic Ocean ([http://www.apl.washington.edu/project/project.php?id=arctic\\_sea\\_state](http://www.apl.washington.edu/project/project.php?id=arctic_sea_state)), sponsored by the U.S. Office of Naval Research, has just completed a unique field campaign to investigate the dynamics of the autumn sea ice recovery in the Arctic.

Our expedition on board the newly commissioned (<https://eos.org/project-updates/a-university-government-partnership-for-oceanographic-research>) R/V *Sikuliaq* collected data on the dynamics of air, sea, and ice from 28 September to 10 November 2015. During this time, the ice edge moved 250 nautical miles southward from the summer ice minimum in the Beaufort and Chukchi seas, reaching the Alaskan coast.

## Making Waves

The field program was designed specifically to understand the effects of an increasingly dynamic sea state (that is, an increase in surface wave activity) on autumn ice recovery (Figure 1).



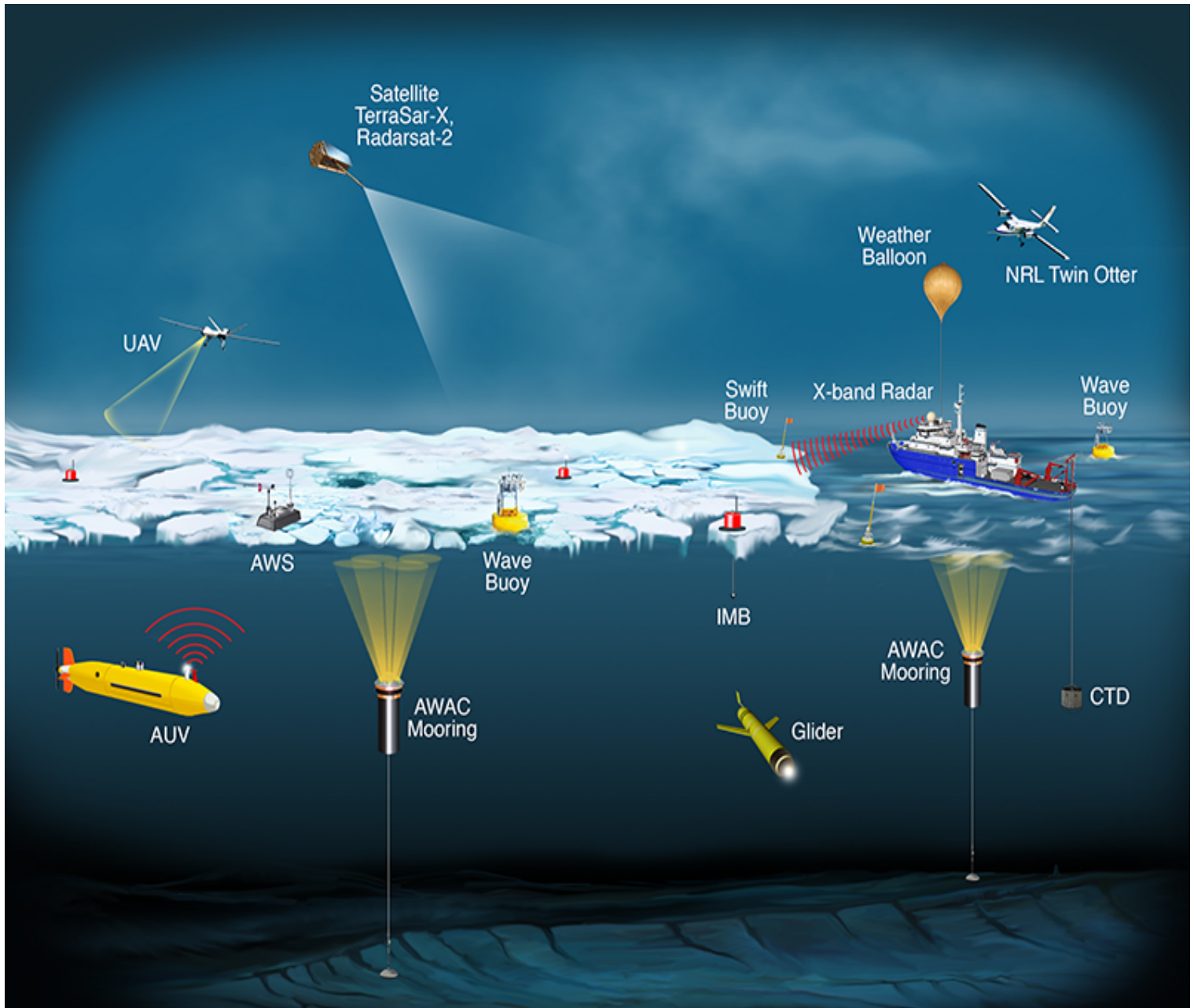


Fig. 1. Instrument platforms used in the Sea State and Boundary Layer Physics of the Emerging Arctic Ocean field campaign include unmanned aerial vehicles (UAV), autonomous underwater vehicles (AUV), automatic weather stations (AWS), Acoustic Wave and Current (AWAC) moorings, and underwater gliders. Various instruments are mounted on buoys and weather balloons, and floating instruments measure ice mass balance (IMB) and conductivity-temperature-depth (CTD) data. X band radar and airplanes are used to map the ice and waves around the ship. Credit: Woods Hole Oceanographic Institution graphics department

The loss of sea ice has not only increased the size of the open sea but also increased the size of the

waves themselves, as surface waves have a greater distance over which they can form and grow. To express this in nautical terms, fetch has increased [*Thomson and Rogers, 2014*].

This effect is most pronounced at the end of September when sea ice extent is minimum (<https://eos.org/articles/arctic-sea-ice-extent-may-shrink-below-2012-record-low>) (so fetch is maximum) and wind forcing is generally strong. Over the 6 weeks of the field campaign on board *Sikuliaq*, the simplest observation of all—visual confirmation of pancake ice formation—showed the effect of increased fetch on surface waves (Figure 2).



Fig. 2. A Surface Wave Instrument Float with Tracking (SWIFT) buoy measures waves in pancake ice. Credit: Benjamin Holt, NASA/JPL-Caltech

## Pancake Ice

Pancake ice forms when wave orbital motions (that is, circular wave movements (<https://s-media-cache-ak0.pinimg.com/originals/48/15/08/4815085332efae3fedc4a826a23507ca.gif>)) disturb collections of ice crystals in the water, collectively called “frazil ice,” as the ice forms. Frazil ice is “slushy”—soft and amorphous—because the water is moving too much to allow a solid sheet of ice to form. Quiet waters can form large, thin, flat sheets of new ice, called “nilas,” but the mobilized frazil aggregates

into small floes that float on the sea surface and collide as each wave passes.

The collisions make floes round, such that they resemble pancakes (<https://eos.org/project-updates/drones-in-a-cold-climate>). Because the pancakes are typically 1 meter or less in diameter, they are below the resolution of most satellite imagery. This means that they are observed only from nearby, from ships or airplanes, or by autonomous platforms with cameras.

Pancake ice is relatively ubiquitous in the Antarctic sea marginal ice zone, but it has rarely been observed in the Beaufort and Chukchi seas. However, it was the dominant newly formed ice type that we encountered during this field campaign. We observed pancake ice with far greater regularity during this field campaign than in recent early autumn cruises in the eastern Beaufort (<http://www.whoi.edu/beaufortgyre/expeditions>) conducted through the Joint Ocean Ice Study/Beaufort Gyre Exploration Project.

Clearly, the presence of pancake ice shows that wind events and the surface waves that come with them are important to the autumn ice recovery in the western Arctic Ocean. Wind and wave actions are perhaps also linked to the known trend of younger, thinner ice throughout the seasonal cycle [e.g., *Maslanik et al.*, 2011].

## **Advance, Retreat, Advance**

The prevalence of pancake ice has a large-scale effect on the autumn recovery of sea ice in the Beaufort and Chukchi seas. Figure 3 shows three maps of sea ice over 1 month; the daily progression is even more complex. As the wave motion declined (either in time or space), the pancakes often rafted together and thereby formed larger, thicker sea ice floes. The pancakes then consolidated (or “cemented”) into surface sheets that were rougher than nilas sheets; these sheets of pancake ice aggregates presumably survived and became the winter ice pack.



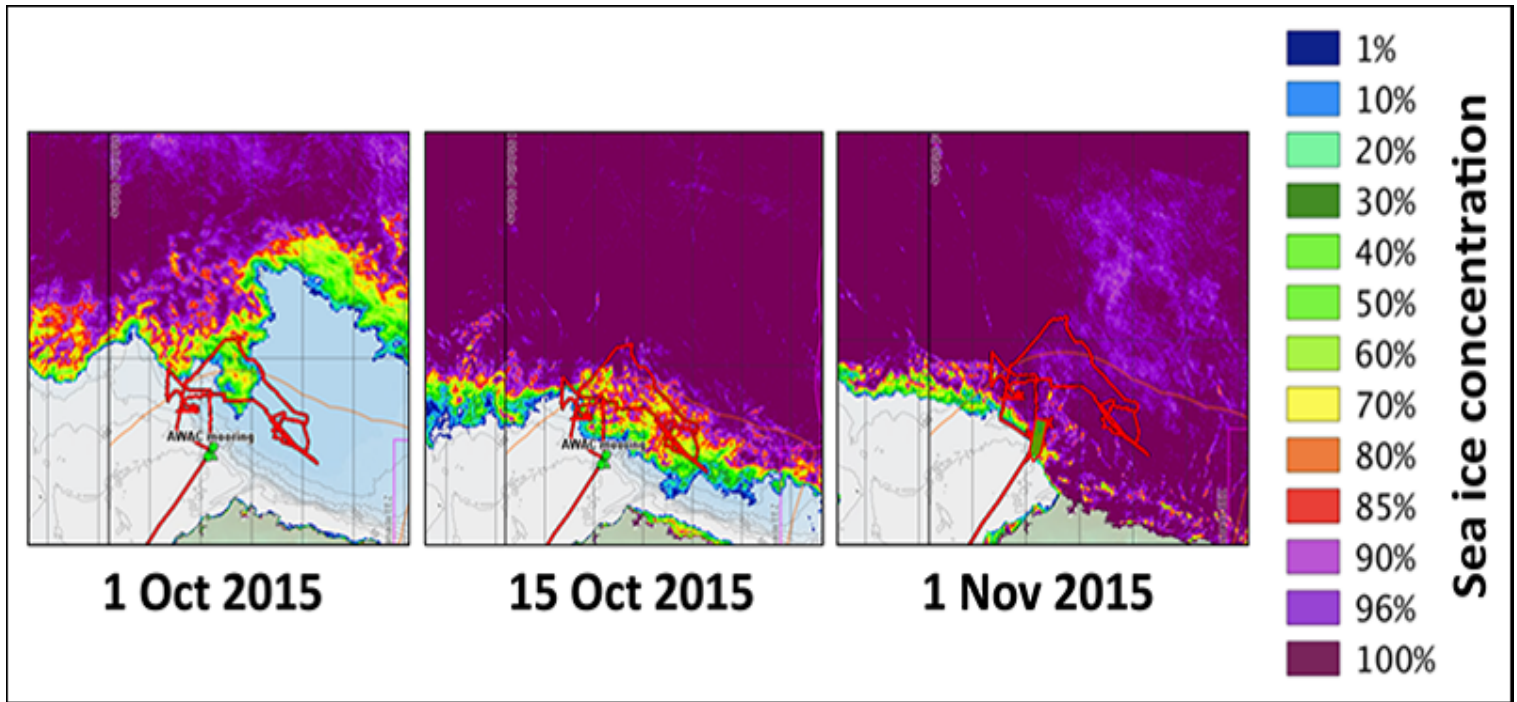


Fig. 3. Ship track (red path), bathymetry (blue shading), and satellite-based ice concentrations (colors, representing the percentage of the area covered by ice in each pixel) showing the recovery of sea ice during the month of October 2015. These images were captured from the map server on board the R/V *Sikuliaq*, which was built and maintained by Steve Roberts of the University of Alaska Fairbanks. Ice concentrations, derived from data from the satellite-based Advanced Microwave Scanning Radiometer 2 (AMSR2), are from the University of Bremen. Credit: Ola Persson (NOAA)

Sometimes, the pancakes' dampening of the wave energy appeared to accelerate this cementing process, which eventually protected the interior pancakes from wave motions and allowed the larger floes to form. In some other events, however, strong wind- and wave-driven mixing of ocean heat prevented the ice edge from advancing, and the pancakes melted in place. Thus, the ice edge advanced one week, retreated the next, and eventually advanced again in an irregular pattern driven by the regional storm cycles.

## Linked Effects from Air, Ice, and Ocean

The autumn recovery of sea ice is the result of a tightly coupled air-ice-ocean system. This system is described by a surface energy budget, which quantifies the flux of heat at the air-ocean interface. If the sea surface loses heat when its temperature is already near freezing, freezing occurs. Colder air

temperatures can enhance ice formation, which we observed on several occasions when winds blew over existing ice and out to open water.

Heat flux from the upper ocean can also counteract or retard ice formation. With larger areas of the Arctic Ocean exposed to the summer Sun, the upper ocean accumulates more heat now than in previous years when it was ice covered for more of the seasonal cycle [Perovich *et al.*, 2007]. This heat is often trapped in a near-surface temperature maximum layer [Jackson *et al.*, 2010]. We observed strong winds and waves mixing this layer upward to the surface.

Diagnosing the freezing process and autumn ice recovery thus requires comprehensive air-ice-ocean measurements (<https://eos.org/features/improving-predictions-of-arctic-sea-ice-extent>), including wave and wind forcing and sea ice transport. Observations from our fall 2015 Sea State field campaign, complemented by satellite, airborne, and shipboard remote sensing observations, are poised to improve our understanding of these processes.

## Planning and Forecasting

The *Sikuliaq* cruise used a dynamic planning strategy that was crucial to adapt to the fast-changing region of our study. Every day, the whole onboard science team participated in updating our plans for the next 3 days, with detailed activities for the day to come and less detailed plans for the next 2 days.

The team based these plans on weather forecasts, wave forecasts performed aboard the ship, and ice data from satellite remote sensing telemetered to the ship by the shoreside team members. Our short-term wave forecasts were accurate in open water but much less so inside the ice cover. The accuracy of the remotely determined ice edge strongly affected the performance of the wave forecast. These forecasts tended to deviate substantially from observations during a strong wind event or rapid ice growth.

## Analysis to Come

The 2015 autumn ice recovery demonstrated the highly interactive nature of ice, wave, atmospheric, and oceanic processes.

We have an enormous set of air, ice, and ocean measurements to analyze, both from the ship and from numerous autonomous platforms employed during the field campaign. The 2015 autumn ice

recovery demonstrated the highly interactive nature (<https://eos.org/research-spotlights/arctic-tides-drive-water-mixing-and-sea-ice-loss>) of ice, wave, atmospheric, and oceanic processes. The winds and waves modulate this ice recovery, which influences, in turn, the interactions between the atmosphere and ocean.

This strongly coupled problem is clearly a massive challenge for the models we use to forecast the ice, waves, ocean, and atmosphere. These interactions cannot be implemented in computational codes before we understand them empirically or, better yet, the underlying physical principles are understood.

Our task now is to use these data to quantify the sea state and ice formation processes. The end goal is to improve prediction for immediate operational use and for long-term climate scenarios. We intend the subsequent model improvements to be useful to both the broader research community and the local communities who live along the Arctic coastline and experience climate change firsthand.

Our results will be published in a special issue

([http://agupubs.onlinelibrary.wiley.com/hub/jgr/journal/10.1002/\(ISSN\)2169-9291/](http://agupubs.onlinelibrary.wiley.com/hub/jgr/journal/10.1002/(ISSN)2169-9291/)) of the *Journal of Geophysical Research: Oceans* that has been approved for 2017.

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## References

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- Jackson, J. M., et al. (2010), Identification, characterization, and change of the near-surface temperature maximum in the Canada Basin, 1993–2008, *J. Geophys. Res.*, **115**, C05021, doi:10.1029/2009JC005265.
- Jeffries, M., J. Overland, and D. Perovich (2013), The Arctic shifts to a new normal, *Phys. Today*, **66**(10), 35.
- Maslanik, J. A., et al. (2011), Distribution and trends in Arctic sea ice age through spring, *Geophys. Res. Lett.*, **38**, L13502, doi:10.1029/2011GL047735.

Perovich, D. K., et al. (2007), Increasing solar heating of the Arctic Ocean and adjacent seas, 1979–2005: Attribution and role in the ice-albedo feedback, *Geophys. Res. Lett.*, **34**, L19505, doi:10.1029/2007GL031480.

Stroeve, J., and D. Notz (2015), Insights on past and future sea-ice evolution from combining observations and models, *Global Planet. Change*, **135**, 119–132, doi:10.1016/j.gloplacha.2015.10.011.

Thomson, J., and W. E. Rogers (2014), Sea and swell in the emerging Arctic Ocean, *Geophys. Res. Lett.*, **41**, 3136–3140, doi:10.1002/2014GL059983.

Wang, M., and J. E. Overland (2012), A sea ice free summer Arctic within 30 years: An update from CMIP5 models, *Geophys. Res. Lett.*, **39**, L18501, doi:10.1029/2012GL052868.

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